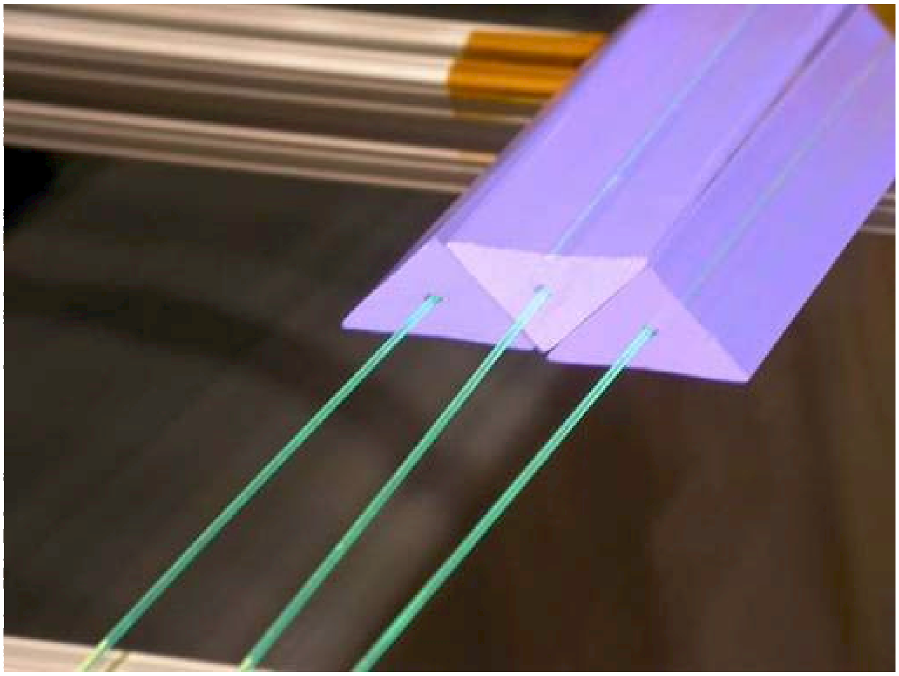

Figure 1: Prototype MINERνA scintillator bars, with wavelength-shifting fibers inserted.

3 The MINERνA Project

3.1 Scintillator Detectors

3.1.1 Overview

This Chapter describes the MINERνA scintillator components for the Inner (ID) and Outer (OD) Detectors, and related systems such as the Vertical Slice Test (VST) and the Veto Wall. Section 3.1.2 addresses the requirements and performance criteria for the scintillator system. Section 3.1.3 provides an overview on the extruded scintillator preparation (WBS 1). Section 3.1.4 describes the wavelength shifting (WLS) fibers (WBS 2) that will be used in the detectors. Section 3.1.5 discusses in detail the clear fiber cables (WBS 4). Section 3.1.6 offers a description of the Vertical Slice Test and its performance.

3.1.2 Requirements and Performance Criteria

The MINERνA detectors utilize extruded plastic scintillator which is read out by wavelength shifting (WLS) fibers coupled to multi-pixel photodetectors. Figure 1 shows early prototypes of the scintillator and WLS fiber system This technique provides excellent energy and spatial resolutions. The baseline design relies on existing technology for which performance measurements have been made. This same system is being used in the MINOS experiment. The major components that will be discussed in this Chapter are:

- The scintillator strips which consist of an extruded polystyrene core doped with blue-emitting fluorescent compounds, a co-extruded TiO_2 outer layer for reflectivity and a hole in the middle for a WLS fiber. These strips are prepared with a triangular cross-section (3.3 cm base and 1.7 cm height) for the Inner Detector (ID) and with a rectangular profile (1.9 cm base by 1.5 cm height) for the Outer Detector (OD). Figure 1 shows an early prototype ID scintillator strip without the white reflective coating and with WLS fibers inserted in the hole.

- The WLS fibers which consist of Y11 fibers manufactured by Kuraray with 175 ppm of dopant, multi-cladded, and a 1.2-mm diameter. These fibers are glued into the hole of the scintillator strips using an optical epoxy (Epon resin with TETA hardener). The fibers are read from one single end. The other end is mirrored.

- The clear fiber cables which consist of ribbons of 8 clear fibers (1.2 mm diameter, 109 cm maximum length) to carry the light from the detector modules to the photodetectors. Optical connectors are used for all fiber optics connections.

The technical requirements on the scintillator system have been established from a combination of physical studies and practical considerations. The technical requirements for the Inner Detector scintillator are more stringent than those for the Outer Detector scintillator. However, in order to save time and money the same scintillator will be produced for both applications. The same co-extrusion procedure with the same raw materials will be utilized. Therefore only the specifications of the Inner Detector Scintillator-WLS-Clear Fiber system are listed here:

Scintillator Bar Specifications:

Cross-sectional uniformity: ± 0.5 mm base and height both, measured with a caliper to within 0.1 mm.

Length uniformity: 5%, must be cut at 1% precision later.

Minimum TiO_2 thickness: .13 mm for efficient light reflection (based on MINOS tests).

Scintillator Light Output Uniformity: 5%, measured to within 1%.

Attenuation Length: 30 cm or longer.

Light Output: The light output must be sufficient for measuring event vertices and multiplicities. We have determined that the number of photoelectrons (pe) per doublet, per minimum ionizing particle: 8 pe with discrimination at the single photoelectron level. A safety factor of 2 is used to account for the variations in the individual scintillator bar light output combined with the transmission through the optical cables and connectors, and the long-term degradation of the light/fiber assembly that is expected.

Fiducial Mass: The total mass in the Fiducial volume of the Inner Detector varies for different physics analyses, but there should be a minimum of 3 tons fiducial mass for each analysis. A minimum transverse (longitudinal) distance of 35 cm (50 cm) is required for containment. For the MINERvA detector, the minimum transverse distance cut translates to a cut of 75 cm maximum distance from the center of the detector.

Uniformity: The light output at the end of the clear fiber should vary by no more than 30% with respect to the nominal location. This ensures that over 99% of the bars will meet the 8 photoelectron requirement.

WLS Fiber Attenuation and Mirroring: The light output at the far end of the scintillator bar must be above the minimum 8 photoelectrons per layer.

Clear Fiber Cable Transmission: The clear fiber transmission should be high enough that the minimum number of photoelectrons at the far end of the scintillator bar is 8 photoelectrons per layer.

Stability: The detector is expected to be able to operate for approximately 10 years, over that time the scintillator-fiber assembly light output is expected to decrease roughly 3+-1% per year (ref: B. Choudhary, NUMI-note 414). Due to this degradation, a safety factor of 1.3 should be included in the light output requirement in order to allow operations over 10 years. Short-term variations must be measurable, at the few per cent level over a month.

Calibration: The detector energy levels must be absolutely calibrated at the 2% level.

Transverse Position Resolution: In order to do exclusive channel reconstruction and make precise vertex measurements the transverse coordinate resolution must be 3 mm.

Linearity: The non-linearity of the Inner Detector scintillator bar system should be less than 15%, and should be known to better than 5% (of 33% of itself).

Cross-talk: The cross-talk between adjacent bars should contribute no more than 10% of the intrinsic position resolution of 3 mm. Given the transverse dimensions of the scintillator triangle base, this translates to a requirement that the cross-talk between adjacent bars be less than 2%.

Longitudinal Vertex Resolution: In order to measure nuclear effects we require less than 10% contamination for any given nuclear target region. This requires that the longitudinal vertex resolution is no worse than 1 cm.

Cost: The cost should be as low as possible given the above requirements.

3.1.3 Scintillator Extrusion

Particle detection using extruded scintillator and optical fibers is a mature technology. MINOS has shown that co-extruded solid scintillator with embedded wavelength shifting (WLS) fibers and PMT readout produces adequate light for MIP tracking and that it can be manufactured with excellent quality control and uniformity in an industrial setting. MINERνA intends to use this same technology for the active elements of its detectors. While in terms of size MINERνA pales in comparison to MINOS, its system is similar in scale to other successful applications such as the K2K SCIBAR detector. Extrusion will also enable the use of different cross-sections throughout the detector to better address the experiment needs.

The extruded scintillator elements will be produced at Fermilab using the extrusion line jointly operated by Fermilab and the Northern Illinois Center for Accelerator and Detector Development (NICADD) at Northern Illinois University (NIU). NIU physicists and mechanical engineers have formed a collaboration to support development of the next generation of detectors at Fermilab's Scintillator Detector Development Technical Center. The extrusion line was purchased by NICADD in 2003. The co-extruder line was purchased by Fermilab in 2005. Fermilab and NICADD support and operate the extruder to ensure that the High Energy Physics community has access to affordable extruded scintillator. Fermilab and NICADD personnel have been responsible for commisioning the extruder; simulations, production and prototyping of dies associated with specific detectors; and productions of extrusions for prototypes and detector construction.

MINERνA has chosen a scintillator bar with a triangular profile and a hole in the middle for the Inner Detector (ID). The triangle has a 3.3-cm base and a 1.7-cm height, and a 2.6-mm hole for the WLS fiber. A drawing with the specifications and tolerances for this part is available (FNAL Drawing Number: 9291.000-MB-241845). A rectangular cross-section with a hole in the middle was selected

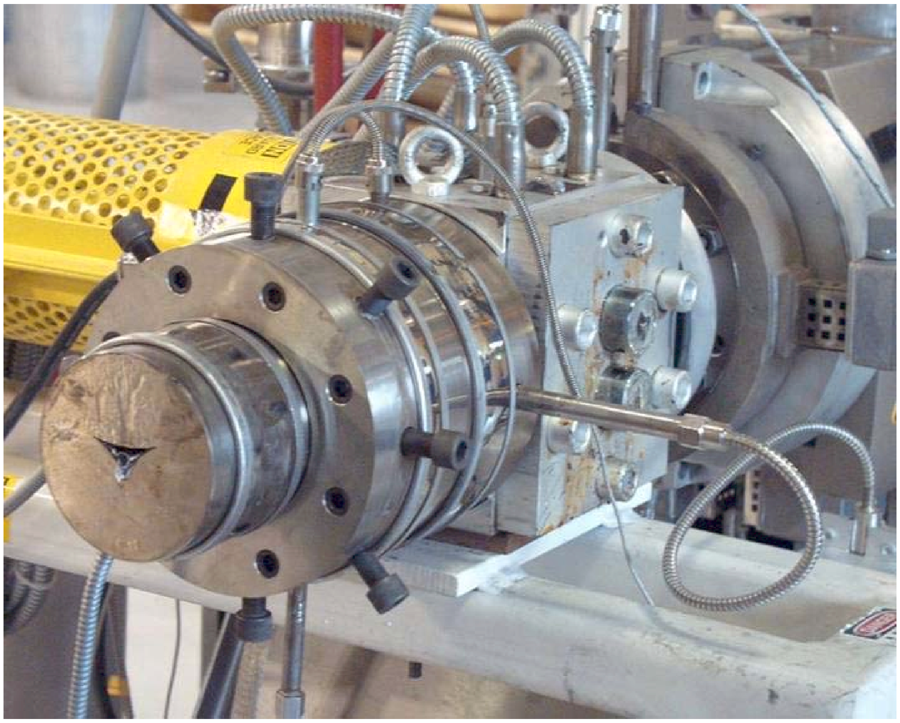

Figure 2: Die to produce MINERνA's triangular strips for ID scintillator.

for the Outer Detector (OD). The rectangle has a 1.9-cm base and a 1.5-cm height, and a 2.6-mm hole for a WLS fiber. A drawing with the specifications and tolerances for this part is available (FNAL Drawing Number: 9219.000-MB-241843).

Figure 2 shows the die for the ID scintillator strips mounted on the extruder. Figure 3 shows the die sections to produce the the OD scintillator strips. Only the last sections of the die and the sizing tooling need to be changed to produce either strip type. All scintillator strips have the same composition: a polystyrene core (Dow Styron 663 W) doped with PPO (1% by weight) and POPOP (0.03% by weight). Both strips have a white, co-extruded, 0.25 nm thick TiO_2 reflective coating. This layer is introduced in a single step as part of a co-extrusion process. The composition of this capstocking is 15% TiO_2 (rutile) in polystyrene. In addition to its reflectivity properties, the layer facilitates the assembly of the scintillator strips into modules. The ruggedness of this coating enables the direct gluing of the strips to each other and to the module skins which results in labor and time savings for the experiment.

The scintillator bars production process is characterized by an ”in-line”, continuous extrusion process as opposed to a batch process. The polystyrene pellets are dried in a nitrogen atmosphere and automatically conveyed to a gravimetric feeder. The dopant mixture is added periodically to a different gravimetric feeder that works surrogated to the pellet feeder. This feeders have the necessary precision and reliability to ensure a constant ratio delivered. The pellet feeder is controlled by computer to the output of the twin-screw extruder to ensure the correct composition and processing. The extruder is responsible for melting and mixing the polystyrene pellets and the dopants. A twin-screw extruder will provide the highest degree of mixing to achieve a very homogeneous

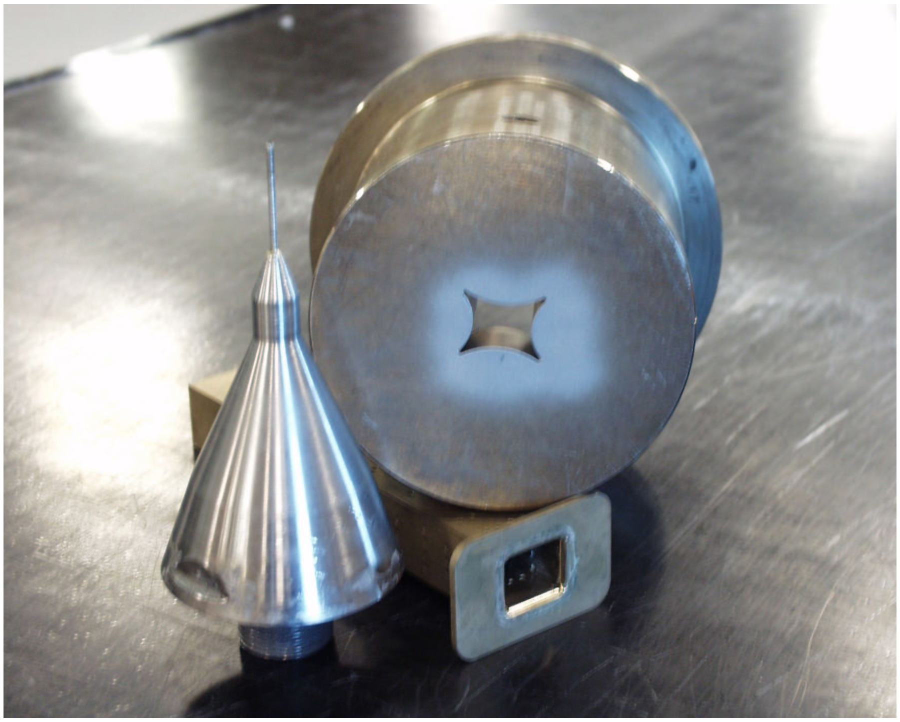

Figure 3: Die to produce MINERνA's rectangular strips for OD scintillator.

concentration. The outer reflective coating is added through material injected from a second extrusion machine (co-extruder) which mixes the polystyrene and TiO_2 pellets. Currently the co-extruder is manually operated to start-up and to vary the thickness of the reflective coating. As the plastic emerges from the die, it goes directly into the cooling tank. There it is formed into the final shape using the sizing tooling and vacuum. It continues to be cooled with water and air until it can be handled.

A total of 13,312 triangular strips and 2,736 rectangular strips will be produced for the ID and OD, respectively. The ID bars will be cut at 3.8 m long and the OD bars at 3.5 m long. Each strip will contain two strips for the final detector module. By cutting a single strip into two sections, it is possible to minimize the amount of waste material and still have each strip of exactly the right length for its hexagon location.

The extrusion rate for both scintillator strips is of 75 Kg/h. The dies have also been tested at 50 and 100 kg/h. There is little difference in the quality of the extruded bars at any of these three rates. However, it becomes harder to cool down the extruded part as the extrusion rate increases. The best compromise is reached with the 75-kg/h extrusion rate. The schedule was develop with the possibility of using the lower rate (50 kg/h) in case that either the overall process (extrusion and quality control activities) or the quality of the material would require it. The higher rate (100 Kg/h) could be used if the production is delayed or if there are personnel shortcomings as a means to keep within the projected schedule. The 23 metric tons of extruded scintillator for the full MINERνA design will require a production run of approximately 18 weeks.

Quality Assurance and Quality Control (QA/QC) procedures to ensure the light yield of the fin-

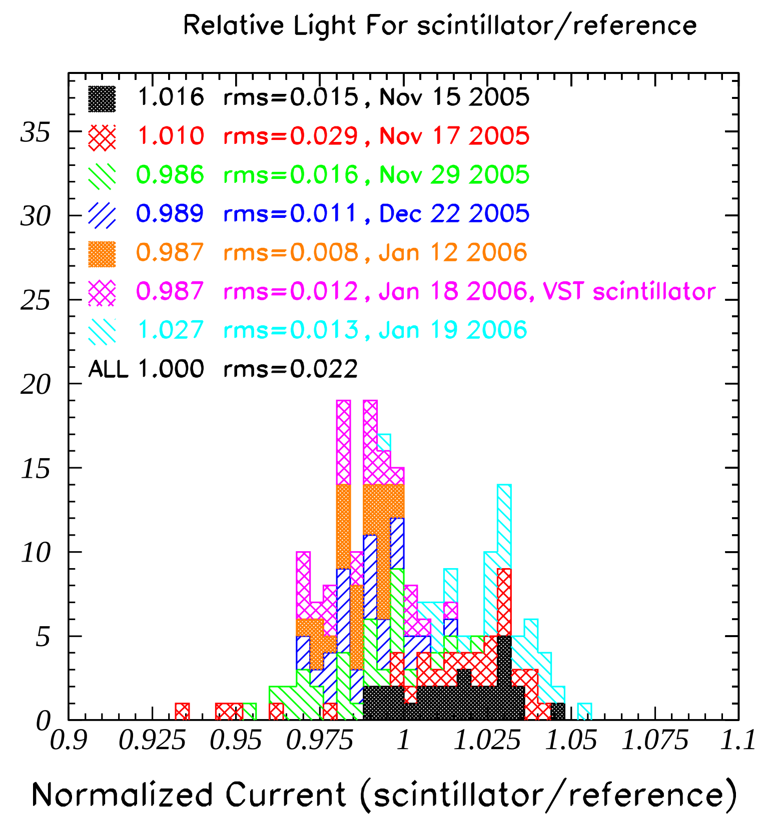

Figure 4: Light yield quality control measurements of the MINERνA scintillator bars. The plot shows the sample measurement divided by the control measurement. The normalization is set to 1. The VST scintillator is labeled. The bottom number shows the RMS of all the bars.

ished product will be established and maintained by Fermilab and NIU personnel throughout production. Figure 4 shows the quality control measurements for seven of the R&D extrusion runs to prepare co-extruded scintillator bars.

3.1.4 Wavelength-shifting fibers

MINERνA optical system uses 1.2 mm diameter, 175 ppm Y-11 doped, S-35 multiclad fiber from Kuraray. Kuraray fibers have a proven track record in many HEP experiments including CDF Plug Upgrade, CMS HCAL, MINOS ... The S-35 denotes a more flexible fiber than non-S fiber, which MINOS and the CDF Plug Upgrade used in their scintillator planes.

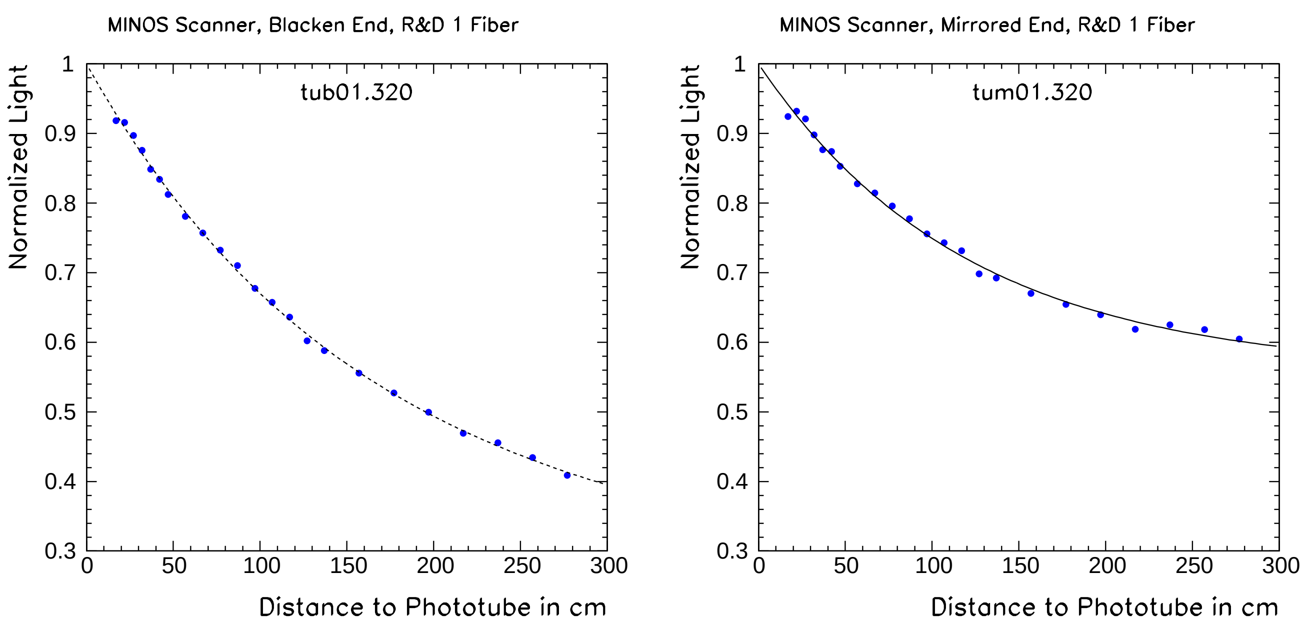

Figure 5: The measurement of the same fiber using the MINOS Scanner. The fiber is first measured with the mirror on. Next, the mirror is cut off and the end painted black. The fiber is remeasured. The fit is a double exponential, $p(1)e^{-x/p(2)} + p(3)e^{-x/p(4)}$, where x is the distance to the phototube and p(i) are the parameters. The mirror reflectivity is determined by using these 2 fits extrapolated to the fiber end.

The fibers will be delivered in batches. A batch is technically called a preform. A small sample of fibers from each batch will be tested using a fiber scanner, called the MINOS Scanner, to determine if the attenuation length is acceptable. The fiber is inserted into a long scintillator, a source moves over the scintillator, and the fiber is read out using a R580-17 Hamamatsu PMT. The PMT is connected with a picoammeter. The data are fit to a double exponential. Figure 5 shows the same fibers measured with mirrored and blackened ends. The quality control will be based on the amount of light at 320 cm from the readout end and the attenuation length. (Note, the longest WLS fibers in

MINERνA is about 320 cm.) Each of these is determined by extrpolating a fit to 320 cm. Figure 6 shows the relative lights among the fibers at 320 cm. The three batches we have received are shown. Figure 6 also show the light loss after 320 cm of fiber. Figure 6 shows that the 3 batches appear to be equivalent.

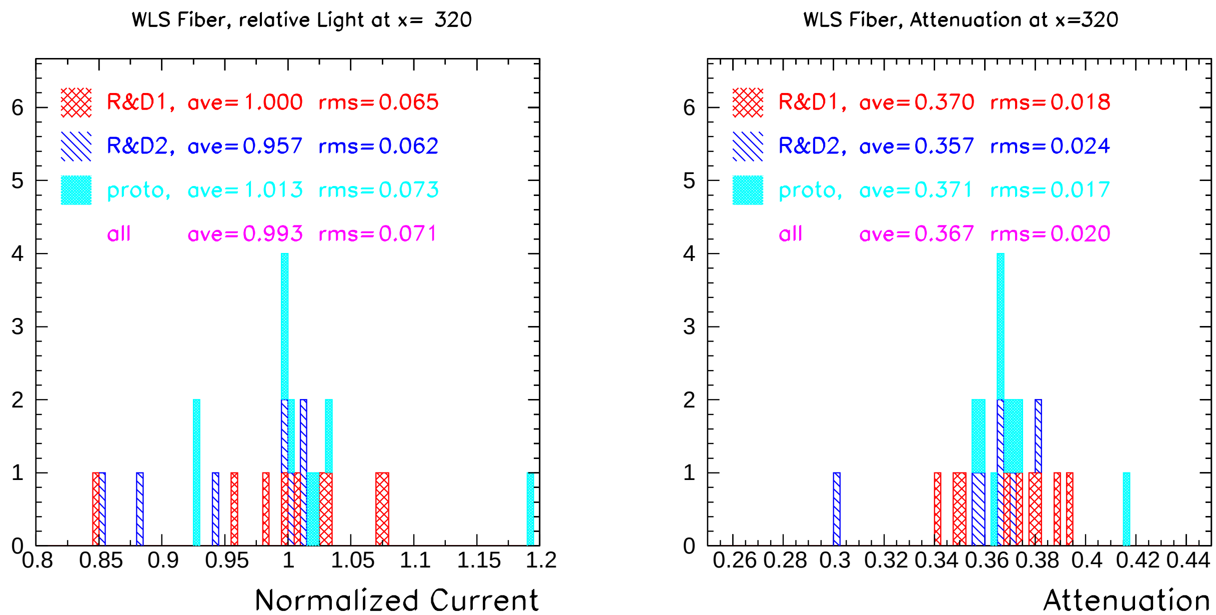

Figure 6: The left figure shows the relative light for the WLS fibers measured with the MINOS Scanner. 3 batches were measured; R&D 1 fiber (purchased May 2005), R&D 2 fibers (purchased Aug 2006), and prototype fibers (purchased Dec 2006). The relative light was normalized to the R&D 1 fibers, the fibers used for the VST. The right figure shows the light loss at 3.2m

MINERνA will read-out only one end of its wavelength-shifting (WLS) fibers. To maximize light collection, we will mirror the unread end of each fiber using techniques developed at Fermilab. "Mirroring" consists of 3 steps: polishing the end to be mirrored, depositing the reflective surface on the fibers (a process called sputtering), and protecting the mirrors.

A technique called ice-polishing is used to prepare the fibers prior to applying the reflective coating. Ice-polishing can give a very good finish to many fibers at once. This technique is described in detail in [1].

The reflective coating is applied in a vacuum system dedicated to optical fiber mirroring at Fermilab. The number of fibers that can be sputtered per load depends on the diameter, but typically 1000–2000 fibers per pumpdown per unit can be coated. A 99.999% chemically pure aluminum coating is a applied for good reflectivity. The coating is approximately 2500 Angstroms thick and is monitored using an oscillating quartz crystal sensor device. The aluminized ends are protected with a coat of epoxy.

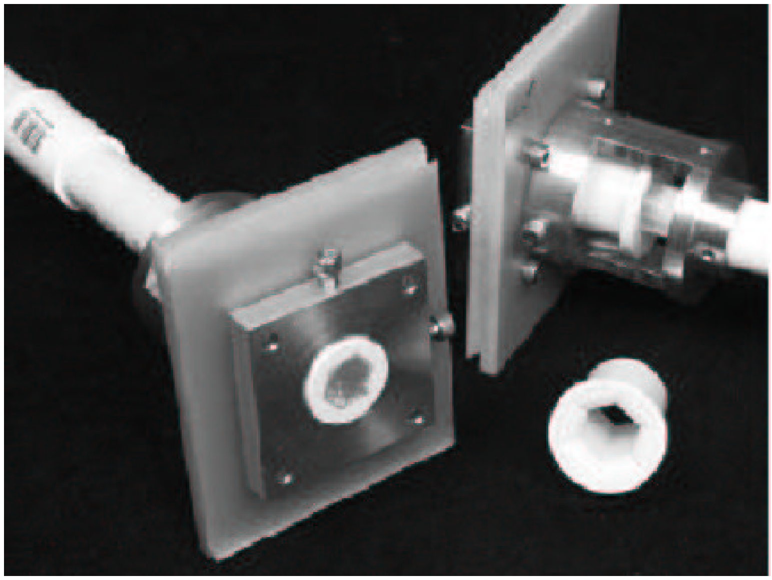

Figure 7: A urethane fixture in an aluminum/G10 frame for holding optical fibers during ice-polishing.

After this process, MINERνA will do a destructive measurement of the mirror reflectivity with production fibers. Light output is measured through the unmirrored end of a fiber with ultra-violet light incident on the fiber near the mirrored end. Then, the mirrored end is cut off at 45°, painted black, and the light yield is remeasured with the UV light at the same place. Figure 8 shows the mirror reflectivity by scanning with the MINOS Scanner the same fiber with and without the mirror.

3.1.5 Fiber connectors and optical cables

We are using optical connectors from Fujikura/DDK (generically referred to as DDK connectors). These connectors were originally developed for the CDF Plug Upgrade by DDK, in consultation with Tsukuba University. Since then, they have been used by several other experiments such as FOCUS, STAR, and D0.

The DDK connectors consist of a ferrule, clip, and box (Figure 9). They snap together without screws or pins. These connectors were chosen for their ease of use. DDK has made a new ferrule die for our 1.2 mm diameter fibers, keeping the outside dimensions of the ferrule identical to the current model; thus, other parts of the connector do not need to be redesigned.

The hole position, diameter, and outer dimensions of the new ferrule have been precisely measured. These measurements were done at SIDET using the CCM and the OGB. (The CCM measure objects mechanically, while the OGB measures objects optically.) When the connectors are mated, the fiber holes line up to < 25 microns. The hole diameters are very similar, with the differences $<$ 12 microns. The ferrules fit very tight in the box. The fit is tight enough that we have asked DDK to redesign the ferrule mold for a looser fit.

The transmission was measured using the new connectors. We injected light into a pigtail using

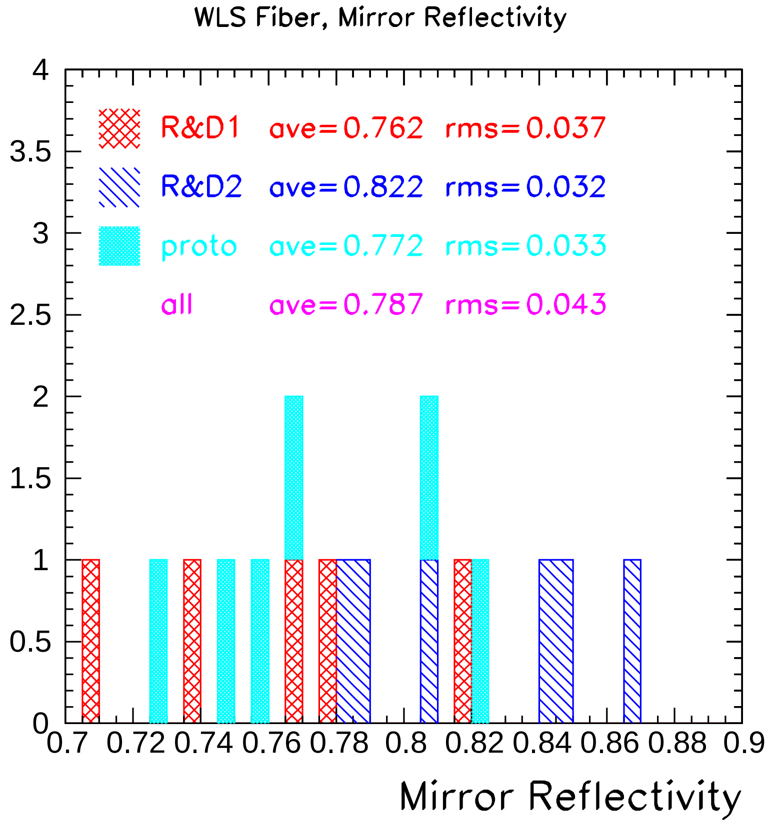

Figure 8: Plot shows of the mirror reflectivity for the 3 batches of fiber. Each batch was mirrored at a different time. Each entry is ratio of a fit to the mirrored fiber and fit to blacken end fiber extrapolated to the mirrored end.

1 m WLS fiber inserted into 0.5 m coextruded scintillator. (By ”pigtail”, we mean a set of fibers put in one DDK optical connector with no DDK optical connector on the other end.) A source excited the scintillator. The light was readout using a PMT and picoammeter. We measured the light before and after inserting a connector into a 2 m cable. Figure 10 shows transmission for 3 cables.

We have measured the light loss from a 1 m clear cable to be about 33% without optical grease between the connections. We injected light into a WLS pigtail using the same procedure as used to test the cable transmission. We connected the DDK connector on a WLS pigtail to DDK connector on a clear pigtail with the other end going to a PMT. We then inserted a 1 m cable between the 2 DDK connectors and remeasured the system. Figure 11 shows ratio of (after cable/before cable). We are planning on using optical grease between the connectors to increase the transmission. We have measured the light increase from optical grease to be about 16%. If optical grease is put on both connectors, the light loss is about 10%. In order to determine the lifetime of optical grease, we have measured the transmission of 2 greased connections after 6 weeks. We have seen no change in the

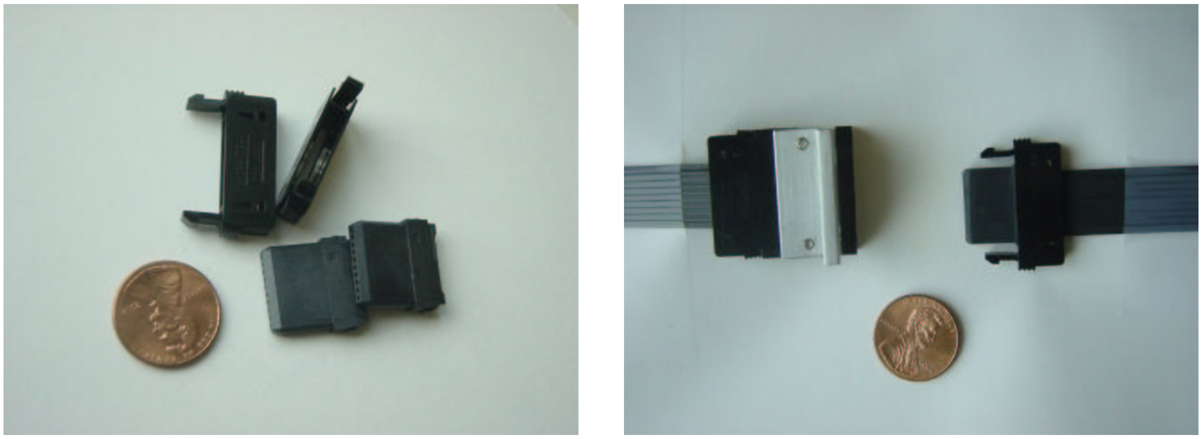

Figure 9: DDK connector parts. At left, examples of the ferrules (bottom) and the clip (top). At right, two completed CDF cables with the box to which they connect. The aluminum angle bolted onto the box is used to hold the box on an aluminum cover.

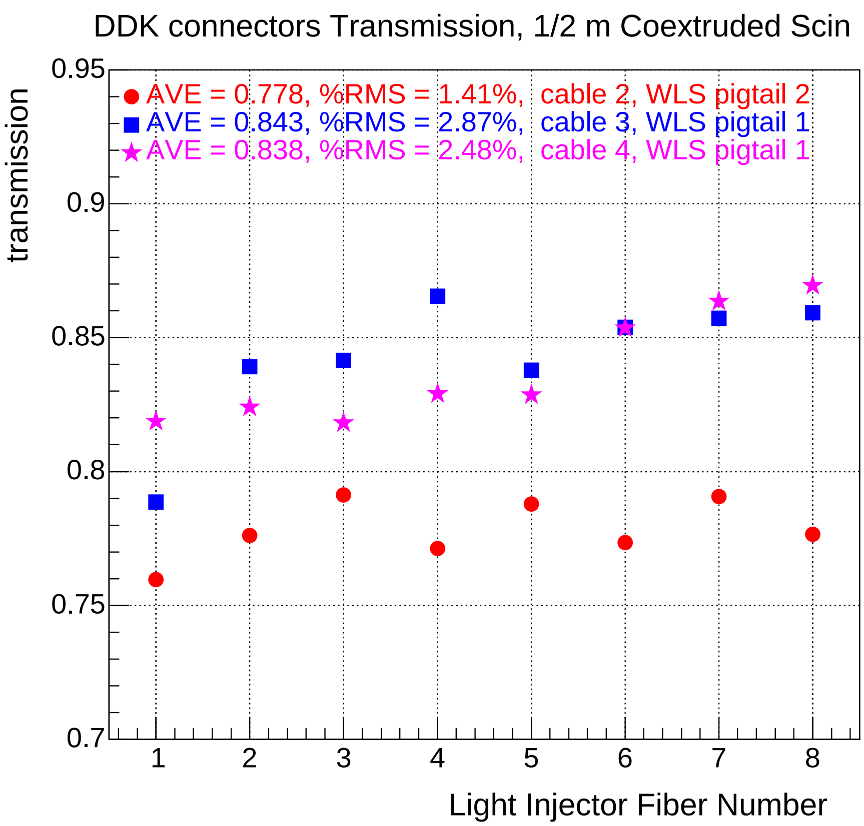

Figure 10: The light transmission for 3 DDK connectors.

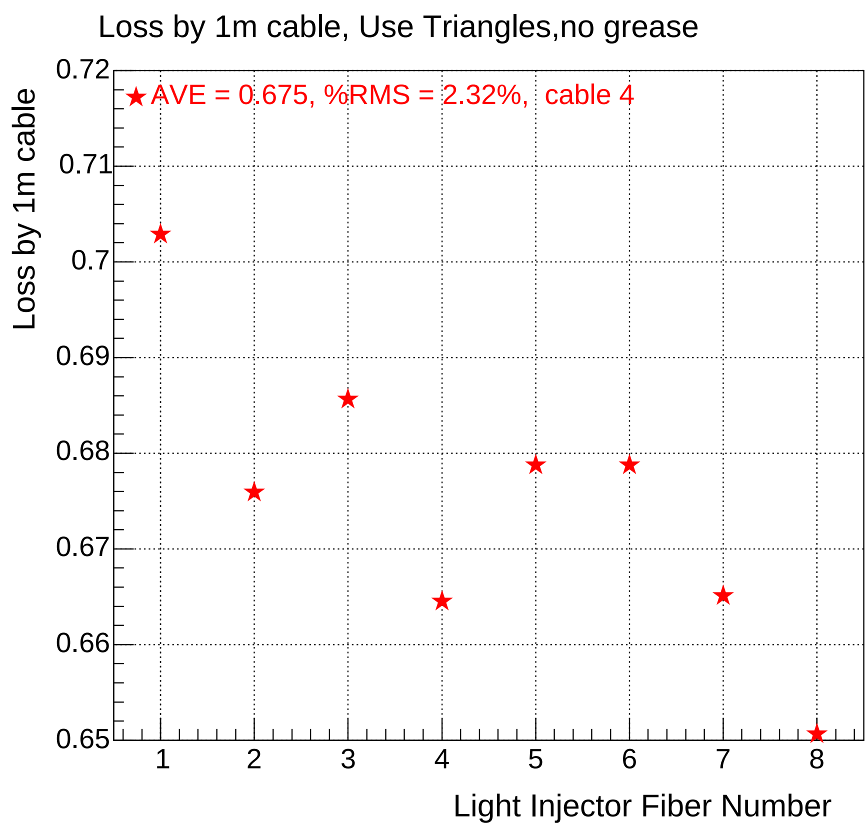

Figure 11: The measurement of the light loss from a 1 m clear cable

light transmission.

For the cables, we are using 1.2 mm, S-35 multiclad fiber from Kuraray to match the Kuraray WLS fiber. The S-35 denotes a more flexible fiber than non-S fiber. A sample of fibers from each batch will have their attenuation length checked using a cut back test developed by CMS. The test uses a source, scintillator, and WLS fiber to inject light into the clear fiber. A 6.8m attenuation length was measured for the R&D 1.2 mm fibers using this procedure.

The fabrication and polishing procedure we plan to adopt was used by the CDF collaborations on DDK connectors/cables. Initially, the fibers are cut to the correct length. Then, the fibers are inserted into a ferrule oriented vertically and taped in place, with the mating end pointing down. The top of fibers are taped against a horizontal piece of metal. BC600 epoxy is then placed in the pocket of the ferrule with a syringe. After the epoxy cures (the next day), two clips are placed on the fibers, one for the ferrule that was just epoxied and the other to fit over the ferrule yet to be fixed to the other end of the cable. Also a light-tight tube is placed over the fibers that covers the entire length of the fibers except for approximately 5 cm near the ends where the fibers enter the ferrules. The end of the fibers not glued in the first ferrule are then placed in a second ferrule and epoxied in place. After curing, the fibers on both ends of the cable are trimmed to about 1/8" at the connector in anticipation of the polishing. After the ferrules and fiber ends are polished, the clips are pushed up onto the two ferrules.

For the CDF Plug Upgrade, a significant Fermilab effort was devoted to developing a method to polish the DDK connectors [1]. Since then, Fermilab has developed a machine which can polish multiple optical connectors simultaneously. Fermilab has designed a fixture for this machine to hold 6 DDK connectors. We have used this machine to polish the R&D cables which have been used for a variety of measurements, including the transmission measurement described above.

We have developed a light-tightening scheme similar to one developed by the Michigan State University nuclear physics group, who used DDK connectors in a large electromagnetic calorimeter. The fibers are surrounded by an 1/4" opaque sheath, INSUL #4900/3. We have developed a mold to surround region at the connectors with a light-tight urethane boot. Figure 12 shows a sample light tight cable. Both the boot material and the tubing have passed the FNAL fire safety review. The urethane boot takes about 1/2 hour to cure, so that only $\sim$ 5 molds are needed for production.

The final QC measurement tests the light transmission for each fiber in the connectors. This test uses a light injector box. This box has a LED with a pin diode for normalization. The LED shines on the fibers in a consistent way which can be normalized by the pin diode. Each cable to be checked is connected from this box to a readout box. Fibers in the readout box go to individual pin diodes which are read out using a Keithley 6485 digital picoammeter. In order to bring the individual pin diodes to the Keithley we will use the Keithley 7001 high density switch system and a Keithley 7058 low current scanner card. A LabView program will control the automated readout procedure. Fibers varying more than certain amount from the average will have their cable rejected. Fibers will be checked for breaks or cracks during and at the end of assembly.

3.1.6 Vertical Slice Test, VST

We have done a complete test of the MINERνA system. The Vertical Slice Test (VST) approximates the MINERvA detector by including every stage of the eventual detector, except for the clear fiber

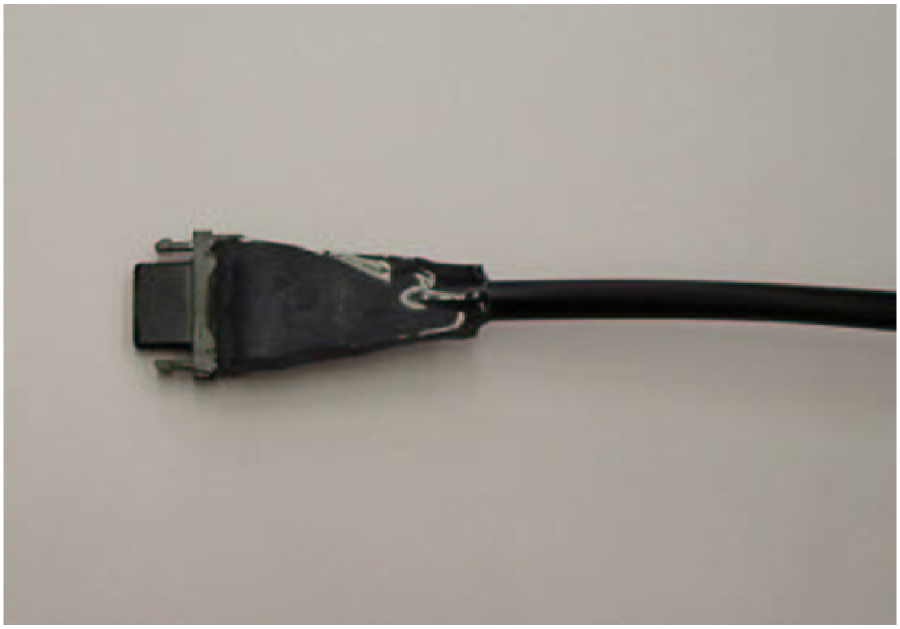

Figure 12: The light-tight boot for DDK connectors.

cables and their connections. Figure 13 shows the optical components of the VST. The VST consists of 3 layers of 0.5 m long scintillator bars. Each layer consists of 7 scintillator bars. The scintillator bars are readout by mirrored WLS fiber (Y11 from Kuraray, 3.5m long, 1.2 mm diameter), identical to the WLS fiber used in MINERνA . The WLS fibers are glued into the scintillator bars using the production MINERνA glue, Epon 815C epoxy with TETA hardener (Epi-Cure 3234). The WLS fibers are glued into optical connectors used by MINOS which are connected to a MINOS CALDET PMT box. The box contains a 64-channel multi-anode PMT. (The CALDET PMT box was used by MINOS for their CERN testbeam.) Coincidence counters are put above and below the array and cover the array to ensure that only cosmic ray muons that pass through the array trigger an event. In addition, a counter some distance from the array insures the muons are perpendicular to the array.

The VST electronics is serving as the first prototype for the MINERνA electronics. The VST prototype boards were designed to be compatible with the MINOS CALDET PMT box and to serve as proof of principle for the proposed daisy-chain LVDS readout system. The VST electronics is composed of four identical boards, each of which plugs into the four 16 channel connectors at the back of the MINOS CALDET PMT box. Since these prototypes were produced before TriP-t chips were available, the TriP chip was used - but this is a nearly identical chip and the additional timing feature, which distinguishes the TriP from the TriP-t is not used by MINERνA . The key features required by the final electronics were present on this first prototype. The VST boards are interconnected by an LVDS link using the same protocol as that proposed for the final MINERνA electronics. Each TriP chip is split with 16 channels used for high gain, and 16 channels used for low gain. The discriminator outputs were routed to an FPGA and the TDC function was implemented in the same way as proposed for the final design. One key feature of the final design that was not tested with

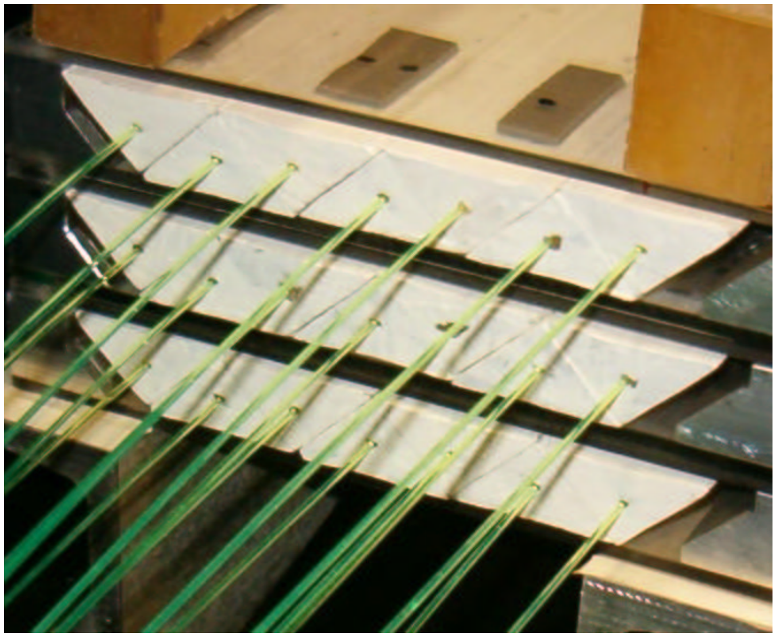

Figure 13: Picture of the VST showing the 3 layers. Scintillator paddles above and below the array serve as the DAQ trigger.

the VST boards was the integration of the CW HV generator with the electronics, because this is precluded by using a MINOS CALDET PMT box, which already has an integrated resistive divider base. However, this was tested using a separate CW generator prototype.

Figure 14 shows the pulse height distribution for cosmic ray muons. In order to determine the single photoelectron (pe) peak, each WLS fiber was pulsed with a LED at a very low light level. Each layer was found to have roughly 6.2 pe/MeV or an average of 21 pe/MIP for a layer. Position was found by weighting strips by photoelectron deposit within a layer. Resolution was found by first averaging layer one and three positions to get a projected position. Next, layer two position was subtracted from that projected position to give a residual. The RMS of the residual for all events divided by the square root of 3/2, which comes from statistics, gives the actual resolution. Figure 15 shows a resolution of 3.2 mm. (Note, the spike at 0 is from events in which all the energy for each layer is deposited in just one scintillator in that layer.)

References

[1] E. Gallas & J. Li., "Polishing Optical Fibers for the D0 ICD in Run II", FNAL-TM-2062, 1998.

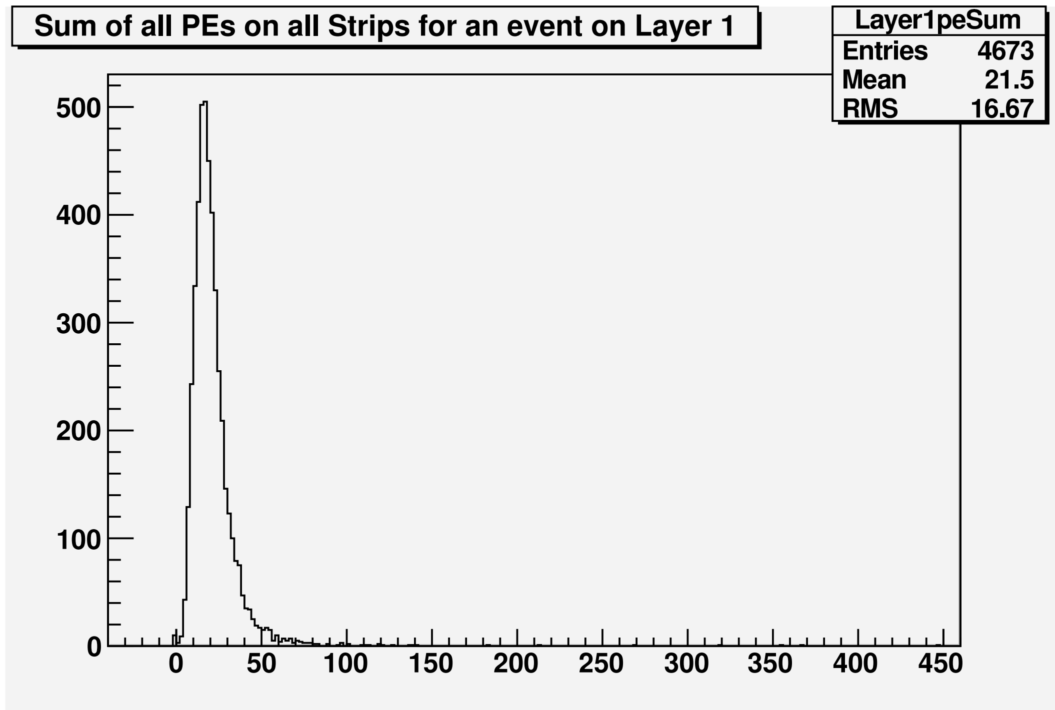

Figure 14: Plot of the pulse height distribution for for muons showing 21.5pe/layer.

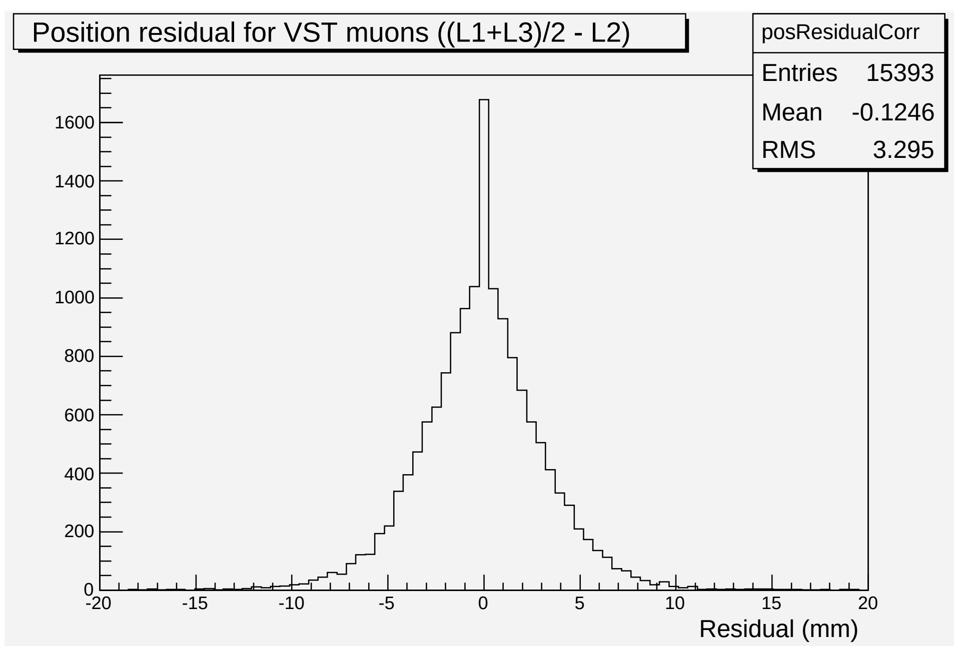

Figure 15: Plots of the $((L1+L3)/2-L2)$ where the "L#"s are the position determined in that layer. The resolution is found to be 3.4mm